FABRICATION AND RECEIVER MEASUREMENTS OF A DIFFUSION-COOLED HOT-ELECTRON BOLOMETER AT 800 GHz

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Abstract

We present a fabrication process for diffusion-cooled niobium hot-electron bolometers using a self-aligned process with gold as an initial protection layer and aluminum as an etch mask that is removed by a wet etch. This process proves to be reproducible and has a yield of ~70 % per batch. Great care has been taken to avoid processing temperatures above 120 °C to minimize degradation of the Nb film.

We have performed heterodyne measurements of an HEB in a fixed tuned waveguide mixer at 804 GHz and at an IF-range from 1-2 GHz. The approximate dimensions of the bridge are 240 x 200 x 14 nm^3. The Niobium bridge has a critical temperature of 6.0 K and a normal state resistance of 16.5 Ω. A standard Y-factor measurement leads to a minimum noise temperature of 1200 K at 1 GHz IF. The coupled LO-power is estimated by the isothermal method to be 21 nW.

Introduction

Superconducting Hot-Electron-Bolometers (HEB) utilizing thin superconducting films have become established as sensitive mixers in the THz region. The thermal response time τ can be very small if the superconductor is thin enough that only the electron gas is heated and the cooling is fast enough. The bolometers described in this paper are cooled by out-diffusion of the hot electrons in normal conducting heat sinks (diffusion-cooled HEB) rather than interactions with phonons of the lattice (phonon-cooled HEB) [1]. To meet the requirements for astronomical applications such as SOFIA, thermal response times down to several picoseconds are needed to get intermediate frequencies up to 10 GHz.

Because of $\tau \sim L^2$ [1] the dimensions of the bolometer bridge have to be very small. We have fabricated diffusion-cooled HEBs with short (L<300 nm) and narrow (<200 nm) bridges consisting of thin (10-14 nm) Niobium (Nb) on z-cut quartz substrates. The normal conducting heat sinks consist of 70 nm Gold (Au). In the following paragraph

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we discuss problems and merits of several approaches for the fabrication of diffusion-cooled HEBs.

Device Fabrication

Aside from a good reproducibility, the essential requirement for the fabrication of a diffusion-cooled HEB is a good transparency of the interface between the heat sinks and the material of the bolometer bridge. A thermal resistance results in a slower out-diffusion of the hot electrons and thus increases the effective bridge length and thermal response time.

Defining the bolometer bridge by lift-off with subsequent deposition of the heat sinks (Fig. 1) [2] has the major disadvantage of high requirements for the overlap accuracy of the Electron-Beam-Lithography (EBL) system to position the heat sinks on the contact areas of the bridge.

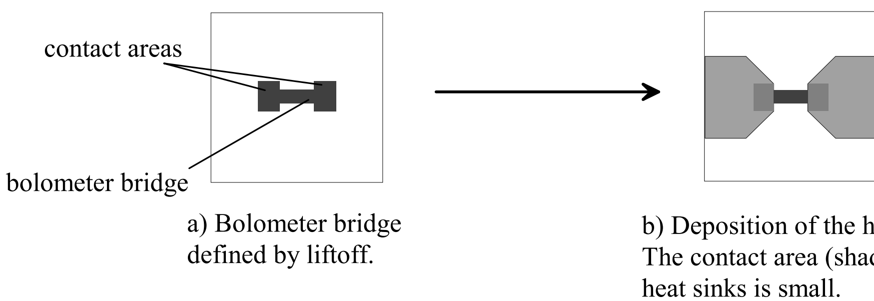

Fig. 1: Outline of HEB fabrication by lift off (top view)

A solution is offered by the self-aligned process (Fig. 2). Here, the substrate is covered with a blanket layer of Nb. The heat sinks and a metal strip of the width of the bolometer bridge are deposited in succession. The bridge is now etched out of the blanket layer by using reactive ion etching (RIE) where the heat sinks and the metal strip serve as etch masks: the spacing between the heat sinks determines the bridge length while the metal strip defines the width. The overlap between Nb and Au heat sinks is large.

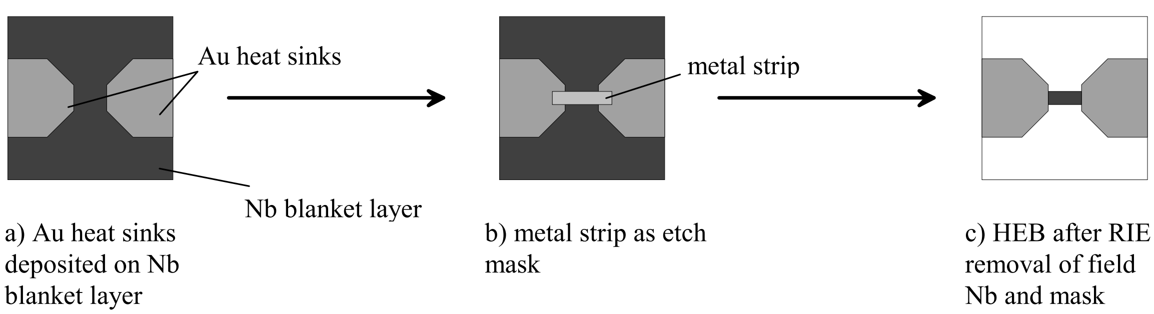

Fig. 2: Outline of self-aligned fabrication process (top view)

A self-aligned process for the fabrication of diffusion-cooled HEBs was developed at JPL [3]. It uses Au as protection layer deposited in-situ subsequent to the Nb blanket layer to prevent the Nb from oxidation and forming a thermal resistance. Au is also used as material of the metal mask for the definition of the bolometer bridge width (Fig.3).
The process requires two gold etch steps which we found difficult to control due to variations in gold thickness after the first gold etch. The second etch step, removing the gold from the bolometer bridge, is then prone to destroy the bridge or leave a Au residue.

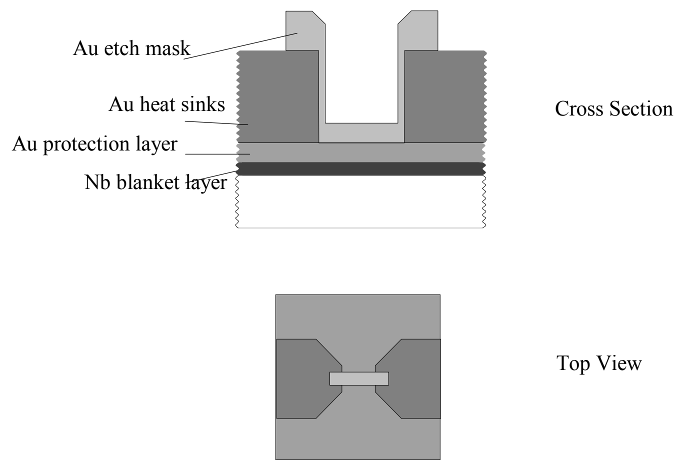

Fig. 3: self aligned fabrication process using a Au protection layer and Au etch mask

In a first effort to solve this problem we tried not to use a protection layer at all. Without a protection this leads to the oxidation of the Nb surface as the wafer is exposed to air. This oxidation layer has to be removed prior to the deposition of the heat sinks, requiring an Ar sputter etch. Unfortunately this clean step turned out to be hard to control due to the small thickness of the Nb film. This lead to irreproducible DC-characteristics of similar-sized HEBs fabricated in the same batch showing contact resistances between 1 to 35 Ohms and irregular resistance versus temperature curves. Hence, the use of an in-situ Au protection layer seems to be crucial for a good transparency of the Nb/Au interface. We chose to change the material of the etch mask from gold to aluminum (Al) to keep the protection layer, distinct from the etch mask, allowing different etch processes for the two layers with good selectivity [4]. In the following we describe the fabrication process that now has been established at KOSMA (Fig. 4).

The small lateral device dimensions down to (100 x 100) nm^2 for the bridge are patterned by Electron-Beam-Lithography (EBL) while larger features above 1 µm are defined using a Karl Süss contact aligner. For EBL we use a 496 K PMMA electron beam resist of 190 nm thickness. All metals are deposited by sputtering. After the deposition of the 12 nm Nb blanket layer and a protection layer of 15 nm Au the heat sinks are defined by EBL, sputtering of 70 nm Au and subsequent lift-off. In a subsequent Ar sputter etch the thin Au protection layer is removed, reducing the thickness of the heat sinks by 15 nm. For a reproducible etch behaviour it is important to avoid intermetallic diffusion of Au and Nb. To this effect we introduced cooling breaks during the Au etch [Tab. 1] and keep the temperature for baking the PMMA at low 120 °C.

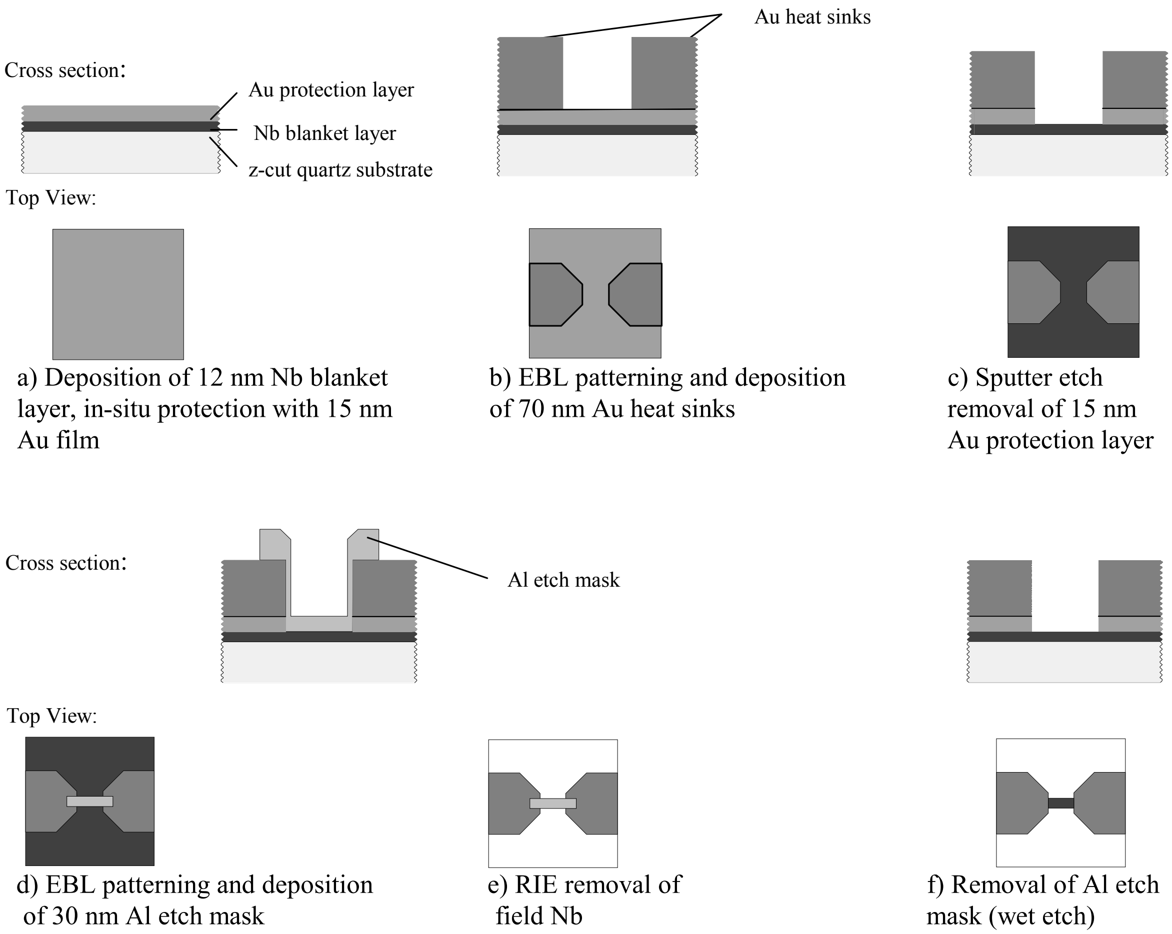

Fig. 4: Self-aligned fabrication process using an Al etch mask

In the next step the Al strip is lift-off defined by EBL and sputter deposition. It is used as etch mask in the subsequent RIE to etch out the bolometer bridge by removing the surrounding Nb. After the definition of the bridge the Al etch mask is removed by a wet etch. We use AZ726 photoresist developer. RF-sputtered SiO_2 is deposited subsequently as a protective coating to avoid degradation of the device by oxidation. The effect of thermal cycling on the coating is unknown.

Material	Process	Process gas	Pressure [Pa]	Flow [sccm]	Power density [W/cm^2]	Duration [min:sec]
15 nm Au	Sputter etch	Ar	4	8	1.1	2 x 0:30 (2:00 cooling break)
12 nm Nb	RIE	CCl_2F_2/NF_3	4	6/1.2	0.13	0:40
30 nm Al	Wet etch	(AZ726)				2:00

Tab. 1: Parameter for Au, Nb, Al etch

The advantage of this process is a very simple removal of the Al etch mask that is rather tolerant against thickness variations of the etch mask. Additionally, the advantage of using a protection layer granting an optimum transparency of the Nb/Au interface is retained. This process offers a high yield of 70-80 % per batch. HEBs of a similar size show similar RT-characteristics (Fig. 5).

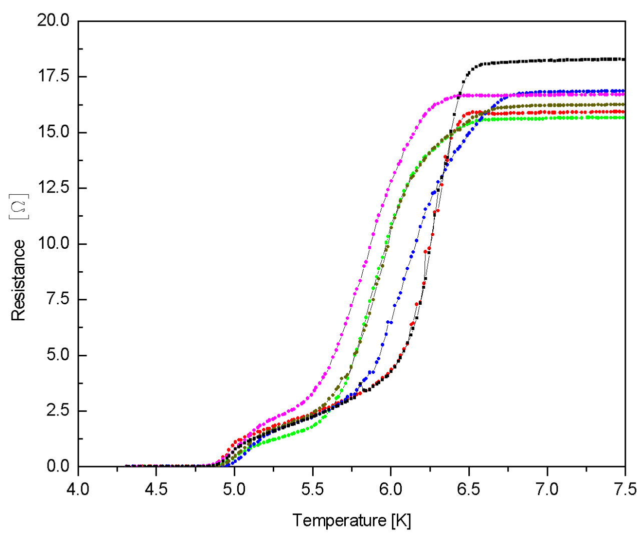

Fig. 5 : RT-characteristics of similar-sized HEBs on one wafer (∅ 22 mm), nominal device dimensions: 240 x 200 x 14 nm^3, R_{sheet}= 14 – 15 Ω. The spread in the R/T curves is probably due to small size variations of the bolometers.

Mixer mount and FTS measurements

The diced quartz substrate carrying the device is lapped down to a thickness of 35 nm and mounted into a fixed-backshort waveguide mixer optimized for performance at 800 GHz [5]. Fig. 6 shows the direct response spectrum measured with a Fourier Transform Spectrometer (FTS). The instantaneous bandwidth from 600 to 980 GHz of the HEB response is determined by the waveguide of the mixer block rather than the device itself.

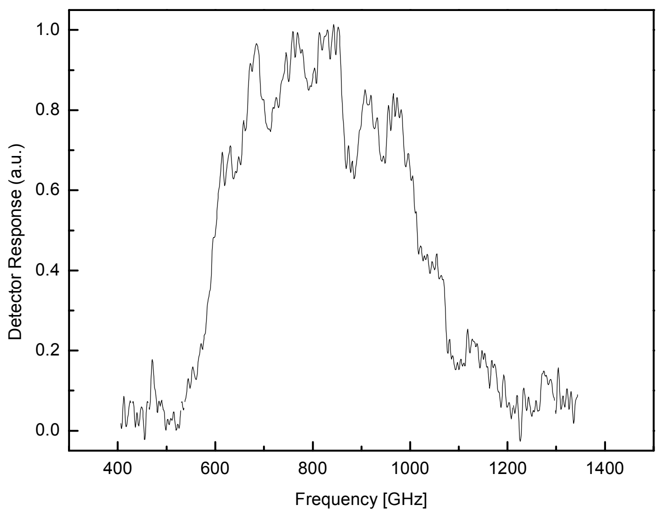

Fig. 6: FTS response of bolometer in fixed-tuned waveguide mount

Heterodyne measurement

For the receiver measurements the LO-signal is superposed with the load-signal with a 36 µm Mylar beamsplitter. A 12 Ohm resistance is connected in parallel with the device. The IF-output is fed through a 50 Ohm coaxial cable to a 1-2 GHz HEMT-amplifier.

The device dimensions and DC characteristics are listed in table 2.

Dev. Dim. [nm^3]	T_C [K]	ΔT_C [K]	I_C [µA]	R_{9K} [Ω]	R_{sheet} [Ω]
240 x 200 x 14	6.0	1.0	230	15	12.5

Tab. 2: Dimensions and DC characteristics of measured device

The device was measured at 800 and 875 GHz at intermediate frequencies from 1-2 GHz. The bath temperature was 4.2 K. The double sideband receiver noise temperature was determined by a standard Y-factor measurement. The LO power requirement was estimated with the isothermal method [6]. Best results are summarized in Table 3.

$T_{Rec, DSB}$ [K]	V_{Bias} [mV]	LO frequency [GHz]	LO power [nW]
1200	0.7	804	21
1500	0.7	875	21

Tab. 3: results of receiver measurement

Fig. 7 shows the LO-pumped and unpumped IV-curve as well as the output power for hot/cold measurements at an LO-frequency of 804 GHz and an IF of 1 GHz.

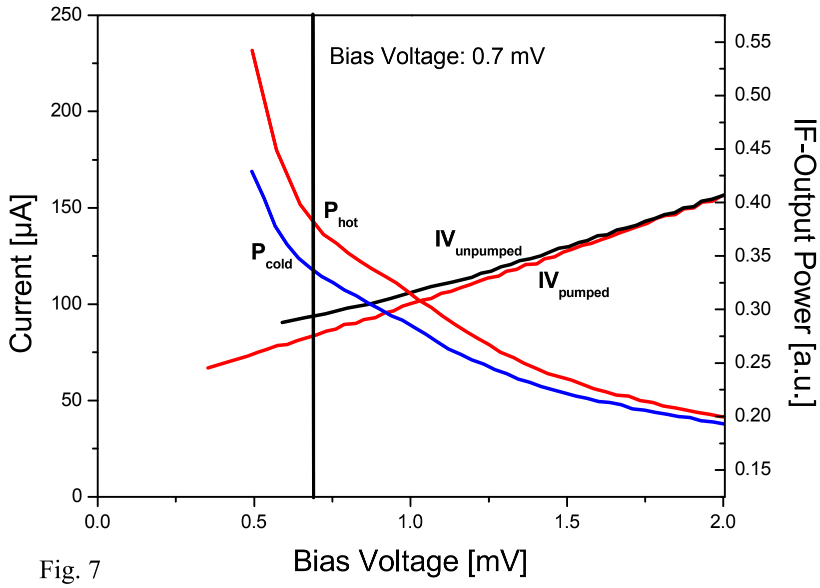

Fig. 7

The bias voltage of 0.7 mV was chosen for stability and did not show any significant shift while changing the loads. Improving the stability of the bias power supply should allow biasing at a lower voltage and thus reducing the noise temperature below 1000 K.

Conclusion

We have established a reproducible self-aligned fabrication process for diffusion-cooled Hot-Electron Bolometers using Al as etch mask. The Al strip can be removed very easily by a wet-etch. A yield of 70-80 % per batch is achieved. First receiver measurements resulted in a receiver noise temperature (DSB) of 1200 K at an IF of 1 GHz.

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